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Effect of battery state of charge on fuel use and pollutant emissions of a full hybrid electric light duty vehicle

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HIGHLIGHTS

- On-road measurements performed on a full hybrid vehicle.
- Data analysis using the Vehicle Specific Power methodology.
- Analysis of internal combustion engine ON and OFF operation.
- Quantify the impact of battery state of charge on fuel use and pollutant emissions.
- Quantify effect of internal combustion engine OFF periods in pollutant emissions.

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ABSTRACT

This research work focuses on evaluating the effect of battery state of charge (SOC) in the fuel consumption and gaseous pollutant emissions of a Toyota Prius Full Hybrid Electric Vehicle, using the Vehicle Specific Power Methodology. Information on SOC, speed and engine management was obtained from the OBD interface, with additional data collected from a 5 gas analyzer and GPS receiver with barometric altimeter. Compared with average results, 40–50% battery SOC presented higher fuel consumption (57%), as well as higher CO_2 (56%), CO (27%) and NO_x (55.6%) emissions. For battery SOC between 50 and 60%, fuel consumption and CO_2 were 9.7% higher, CO was 1.6% lower and NO_x was 20.7% lower than average. For battery SOC between 60 and 70%, fuel consumption was 3.4% lower, CO_2 was 3.6% lower, CO was 6.9% higher and NO_x was 24.4% higher than average. For battery SOC between 70 and 80%, fuel consumption was 39.9% lower, CO_2 was 38% lower, CO was 33.9% lower and NO_x was 61.4% lower than average. The effect of engine OFF periods was analyzed for CO and NO_x emissions. For OFF periods higher than 30 s, increases of 63% and 73% respectively were observed.

1. Introduction

According to SAE, a hybrid vehicle is “a vehicle with two or more energy storage systems both of which must provide propulsion power – either together or independently” [1]. Regarding Hybrid Electric Vehicles (HEV) there are two inboard power sources, namely an electric battery – charged by the vehicle means – and an internal combustion engine (ICE). These vehicles can overcome some of the drawbacks of conventional technologies, namely operation at partial loads, especially on spark-ignition engines. Electric energy is generated by the vehicle means (internal combustion engine, regenerative braking, etc.) and is stored on an on-board electric battery.

There are three basic hybrid electric designs: parallel, series and parallel/series or full hybrid configurations. Parallel HEV available on market use the internal combustion engine and electric motor to move the wheels, with ICE as the main power source and electric assist, according to the driving condition. Battery energy flows to drive wheels via an electric motor that also can act as generator, recharging the battery [2,3]. Series HEV configuration use the ICE as generator and an electric motor to provide movement to the vehicle. This system can run with a small engine output with a stable operation efficiency region, supplying and generating electricity to the electric motor end being efficient in charging the battery [3–5].

In 1997, the Toyota Motor Company launched its mass production hybrid vehicle, the Toyota Prius. This vehicle uses the Toyota

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Hybrid System (THS), adopting a dual configuration, parallel/series design which can be called as "Full Hybrid". This architecture uses a planetary gear set – power split device – that allow the vehicle to be driven only by the ICE, only by the electric motor or by both simultaneously. The 2nd generation of THS, introduced in 2003, compared with similar conventional Toyota's vehicle, represented an improvement in fuel efficiency of 21% [6]. The current THS generation (2009) uses an ICE with 1.8 L capacity, 4 cylinders, Atkinson cycle engine with some electric auxiliaries, such as the water pump for improved efficiency [7]. The full hybrid configuration allows for pure electric drive under certain conditions, hence, ICE can be turned OFF, even while the vehicle is moving. The ICE ON/OFF operation allowed by the full hybrid configuration contributed to qualify this vehicle as the most fuel efficient midsize class vehicle by U.S. EPA in 2012 [8].

Internal combustion engine ON/OFF operation is very important when analyzing energy and pollutant emissions, either in this work using on-road data or during certification. United States HEV certification is based on continuous cycles performing charge sustaining tests (CST), weighted in order to measure exhaust emission and fuel economy [9]. Some approaches quantified the ICE ON/OFF operation defining rules in order to develop a fuel and exhaust emissions model for the full hybrid vehicle [10], concluding that the ICE is usually OFF at combinations of low acceleration and low to moderate speed or moderate speed and low acceleration. It is also OFF in cruising modes at low speed and at deceleration [10], which suggests the practical use of the full hybrid design to avoid the use of the ICE in partial loads regimes.

Hybrid strategy, ICE management, fuel use and emissions are explored in this work, making use of on-road measurements, providing better insight on full hybrid, regarding energy and environmental impacts. On-road data is analyzed using the vehicle specific power (VSP) methodology to provide an estimate of the power per mass (W kg^{-1}) demand, according to vehicle dynamic (speed and acceleration) and road grade. Using VSP methodology is possible to group point of similar power demand and assign the respective fuel consumption rate and pollutant mass rate.

The current research work presents both a macro analysis of energy and emission characterization – independently of the power source – but also focuses on ICE ON/OFF operation, according to the driving demands and battery state of charge (SOC).

The objective of this study is to analyze the impact of battery SOC on fuel use and emissions using the VSP modal analysis. Therefore, on-road monitoring was performed to characterize and analyze the vehicle powertrain in energy and environmental scope, focusing on hybrid energy management, ICE and battery operation, according to the driving conditions and SOC.

2. Experimental

Road test measurements were carried out with a vehicle provided by Toyota Caetano Portugal during 3 days. Data was collected at 1 Hz, using a portable emission measurement system (PEMS), comprehending more than 15,000 s (more than 4 h) of driving data, under urban, extra-urban and highway conditions around the Lisbon metropolitan area, for almost 180 km. Vehicle on-road, regular operation, was collected in 6 trips, each divided in 3 segments.

2.1. PEMS description

A PEMS system was installed in the vehicle in order to collect data in a 1 Hz basis, acquiring engine parameters, state of charge (SOC), exhaust gas composition, road topography and vehicle dynamics [11,12]. Information is acquired from several equipments, connected to a laptop and using purposely developed software. This way was possible to receive, integrate, synchronize and record data along the trips. The ICE data is acquired by a multi-protocol OBD port reader. The information obtained from the OBD port reader are vehicle speed, engine speed and load, airflow mass, manifold absolute pressure, intake air temperature, throttle position and coolant temperature. Battery SOC was also collected from the OBD, using a specific parameter identification code (PID), Hybrid/EV Battery Pack Remaining Charge, defined as "the percent remaining level of charge for the hybrid battery pack, expressed as a percentage of full charge, commonly referred to as State Of Charge (SOC)" [13].

A GPS receiver with integrated barometric altimeter is used to collect latitude, longitude and altitude along the trip for posterior calculation of the road grade. Tailpipe emissions were measured with a portable five gas analyzer. It provides simultaneous information about carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), nitrous monoxide (NO) and oxygen (O_2). Non-dispersive infrared chambers are used to evaluate CO_2, CO and HC concentrations, while oxygen and NO are measured with electrochemical sensors.

Data collected allows estimating ICE fuel consumption and mass of pollutants present in the exhaust in a second by second basis.

2.2. Vehicle Specific Power methodology

The Vehicle Specific Power methodology is commonly used to perform an energy and environmental analysis [14–16]. This analysis provides an estimate of the power per mass unit that is necessary for a driving condition, based on a combination of vehicle dynamics (speed, acceleration, rolling and aerodynamic resistance) and road grade. Thus, each point of the trip is given the correspondent VSP, according to (Eq. (1)).

$$\mathrm{VSP} = v\cdot(1.1\cdot a + 9.81\cdot grade + 0.132) + 3.02\cdot 10^{-4}\cdot v^3 \qquad (1)$$

where: v: vehicle speed (m s^{-1}); a: vehicle acceleration (m s^{-2}); *grade*: road slope (m m^{-1}).

On-road data is grouped in a modal analysis, where each mode has statistically different fuel consumption values and none of them is dominant in the estimation of the trip total fuel consumption, resulting in 14 modes for Light Duty Vehicles [17].

2.3. Vehicle description

The tested vehicle is the 3rd generation of Toyota Prius, 2011 model year, which comprehends Toyota Hybrid Synergy (THS) Drive technology following the concept of full hybrid, providing parallel and series configurations of ICE and electric motor. Different strategies of propulsion could be arranged according to

Table 1
Summary of the characteristics of the vehicles tested.

	Toyota Prius T3 1.8 VVT-I Hybrid E-CVT
Fuel	Gasoline
ICE displacement (cc)	1798
ICE compression ratio	13:1
ICE power (kW RPM^{-1})	73/5200
ICE torque (Nm RPM^{-1})	142/4000
Electric motor type	Synchronous, permanent magnet
Electric motor (kW RPM^{-1})	60/–
Electric motor torque (Nm RPM^{-1})	207/–
Battery type	Nickuel metal hydride (Ni–Mh)
Battery capacity (Ah)	6.5
Battery nominal voltage (V)	201.6
Combined maximum power (kW)	100
Vehicle gross mass (kg)	1725

the needs, changing from electric assist of internal combustion engine, only electric traction or only ICE. This management is done recurring to a planetary gear (Power Split Device) connected to the electric motors and internal combustion [7]. This way, ICE works under defined conditions of high engine load and low specific fuel consumption.

Batteries are recharged under braking situations or when their state of charge (SOC) achieves certain limits then ICE acts as a generator. Spark-ignition internal combustion engine operates under Atkinson cycle configuration, with different compression and expansion ratios, due to variable valve timing. The main characteristics of the vehicle are summarized in Table 1.

3. Results and discussion

3.1. Energy and environmental characterization of on-road measurements

Energy and environmental characterization of the vehicle combine on-road measurements with VSP methodology, allowing summarizing 1 Hz data into a modal analysis of fuel consumption or emission rate characteristic for a given driving situation.

Fig. 1a shows the time distribution at each VSP mode of the on-road measurements. As the VSP mode increases, the amount of

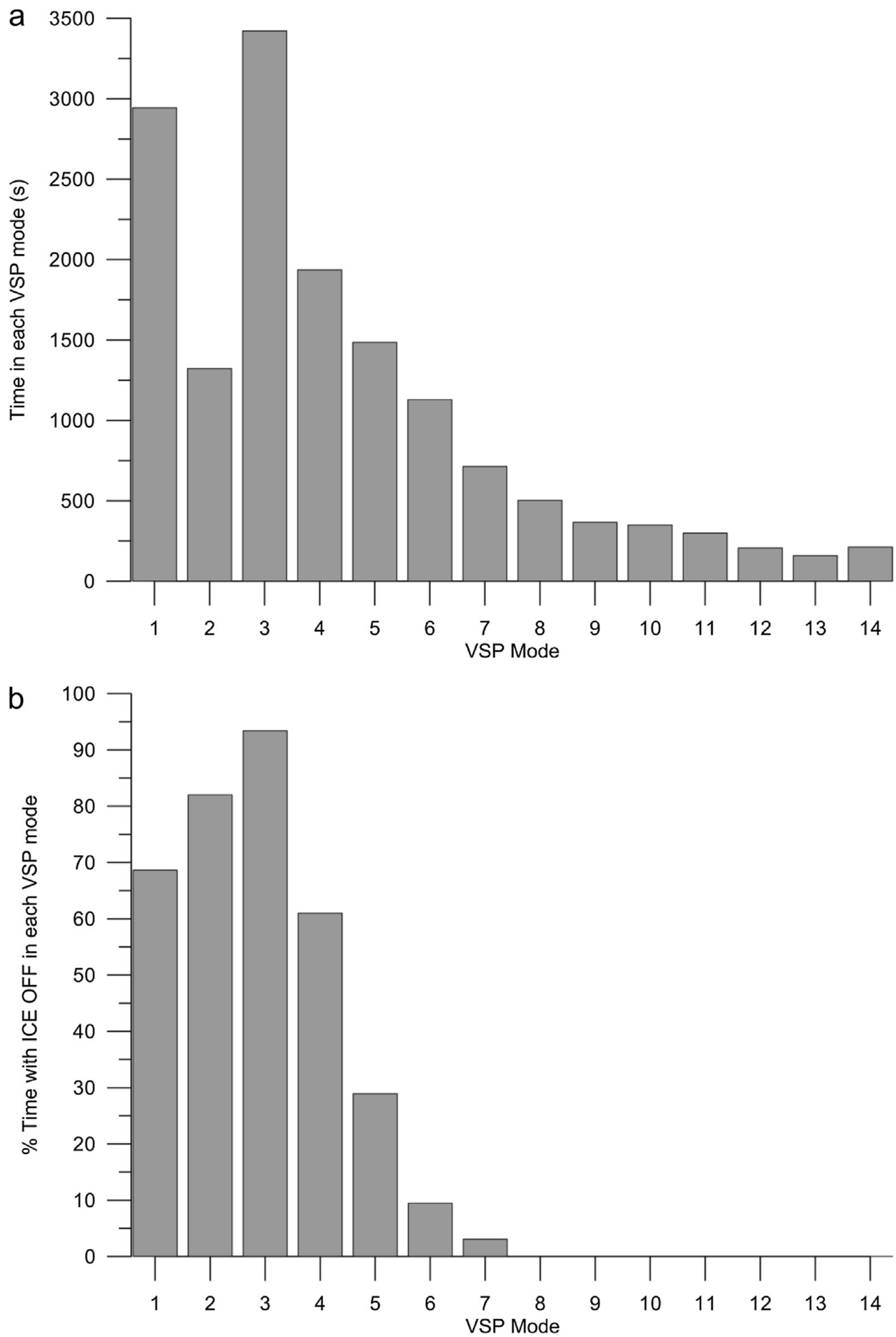

Fig. 1. (a) Time distribution for each VSP mode; (b) Percentage of time with ICE OFF for each VSP mode.

time spent in each VSP mode tends to decrease due to the difficulty of achieving/maintaining high power demands on public roads. Most of the driving time performed corresponds to low VSP modes. For instance, 85% of the total driving time is spent in VSP modes equal or lower than 7 and 95% is spent in VSP modes equal or lower than 11. Fig. 1b shows, for each VSP mode, the percentage of time where the internal combustion engine was not operating (turned OFF). Under these conditions it is said that the vehicle is in pure electric drive (ED) mode. This behavior is a specific case of the parallel/series configuration which is applied in the Toyota Prius. Hence, the vehicle can be moved only by the electric energy stored in the batteries. At the VSP mode 3 (mostly idling points), the ICE was turned OFF around 90% of the time. At the VSP mode 4, it was around 60%, and at VSP mode 5 it was reduced to less than 30% of the time. Full ED function of the vehicle occurs until VSP mode 7 (10–13 W kg^{-1}), which is coherent when analyzing the available electric power (21 kW) and the mass of the vehicle (1725 kg), resulting in 12.2 W kg^{-1}. After VSP mode 7, the ICE is always turned ON. Thus, as power requirements increase, ED mode preponderance tends to decrease.

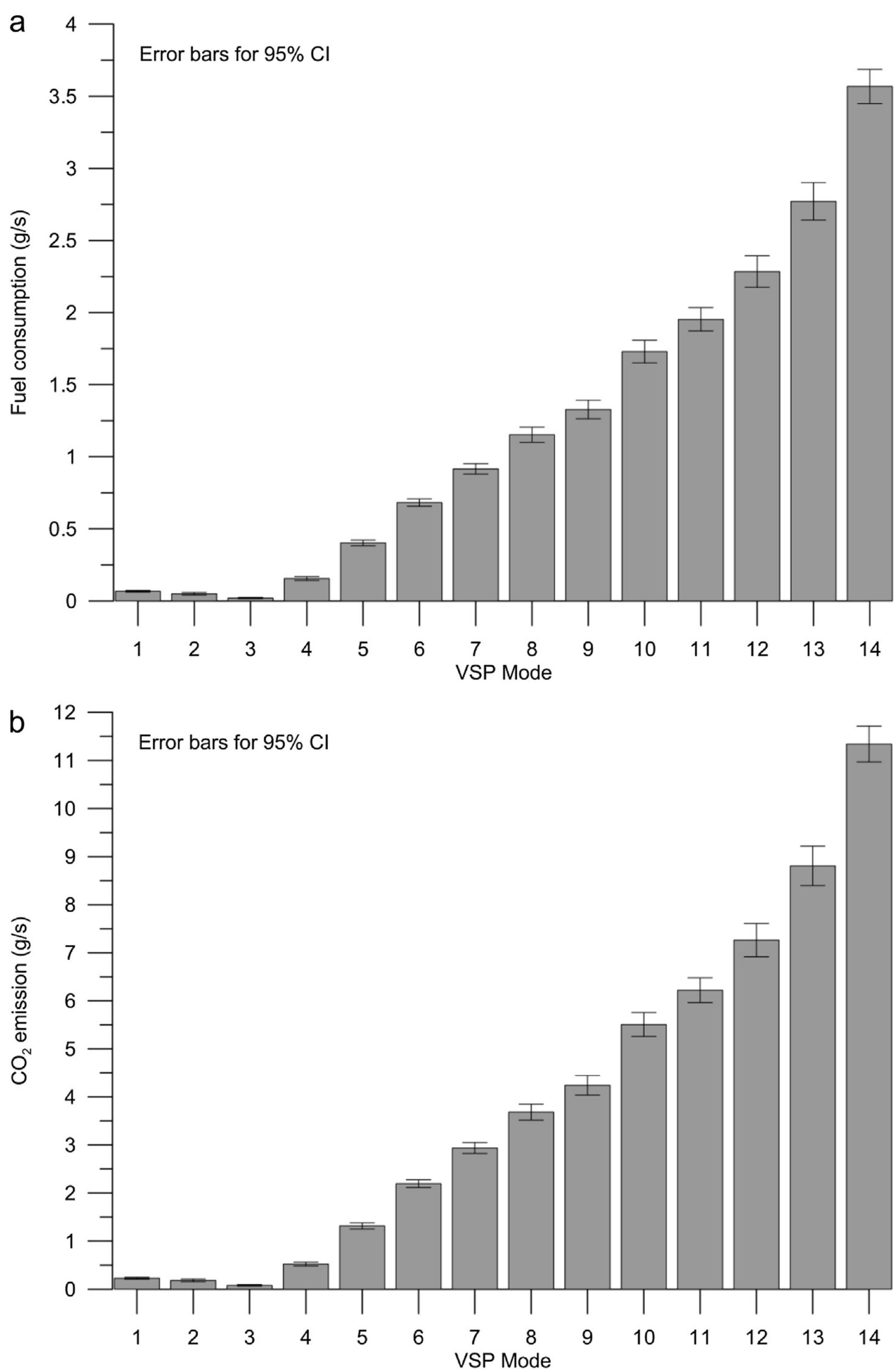

Fig. 2. (a) Fuel consumption (mass flow of gasoline) and; (b) exhaust mass emission rate of CO_2 for each VSP mode.

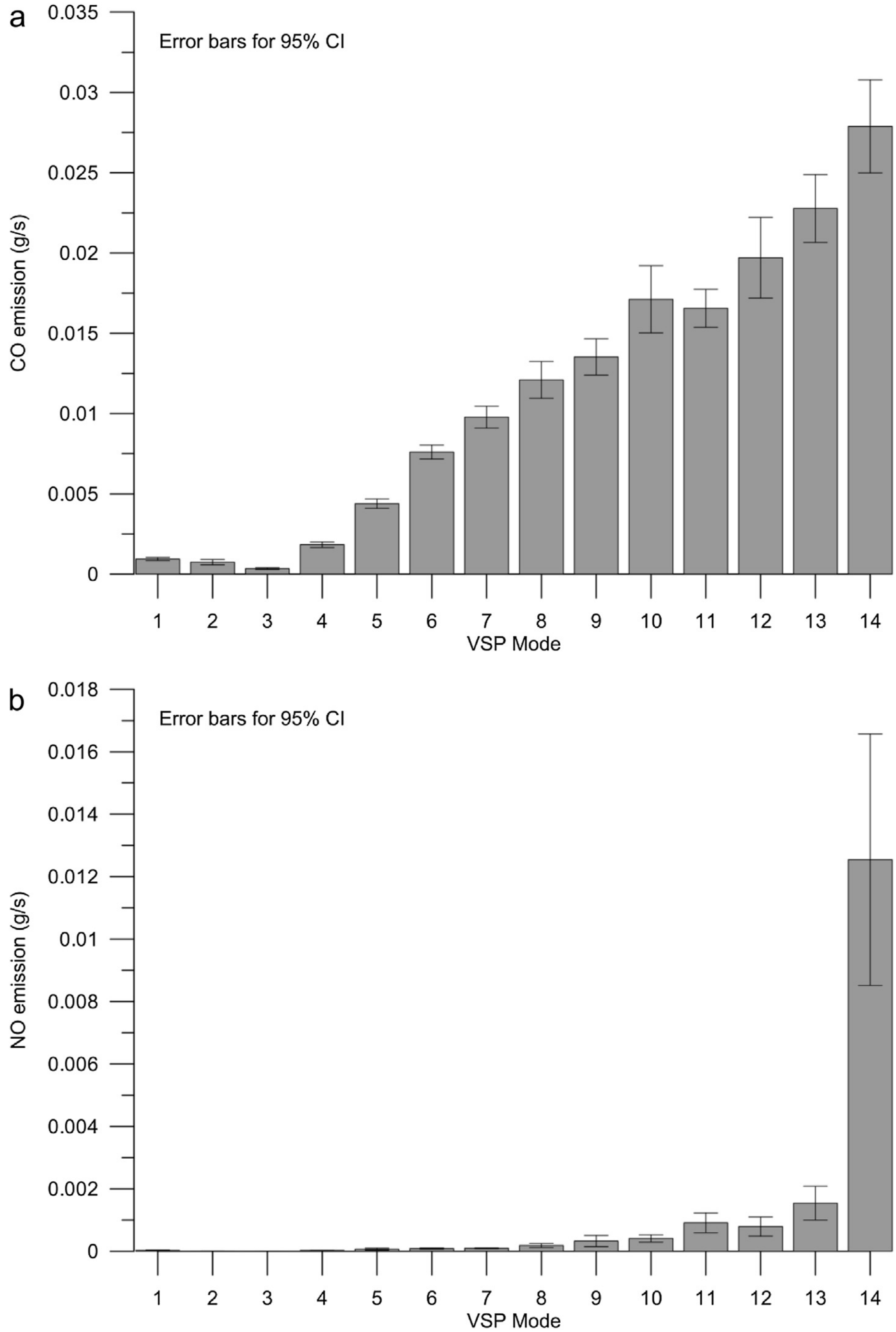

Fig. 3. Exhaust mass emission rates according to VSP mode: (a) CO; (b) NO.

Fig. 2a shows the fuel consumption average mass flow for the 14 VSP modes, considering both ICE ON and OFF operation, analyzing the hybrid vehicle as a black box, just like any other conventional vehicle. As long as the driving conditions are within a given mode, there is no distinction between only electric, only ICE or a combination of both. From Fig. 2a and b it can be seen that fuel consumption (and consequently CO_2 mass emission rates) increase with power demand, particularly for higher VSP modes, where ICE is permanently ON. The impact of ICE OFF operation represents a lower slope of fuel consumption versus VSP mode from VSP 3 to 7

Table 2
Time distribution (in seconds) for each VSP mode for NEDC.

VSP mode	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Time (s)	149	50	338	317	164	48	69	25	6	12	7	0	0	0
Cumulative distribution (%)	12.6	16.8	45.3	72.1	85.9	90	95.8	97.9	98.4	99.4	100	100	100	100

(0.074 ± 0.051 (g s^{-1}) VSP^{-1}), compared with VSP 8 to 13 (0.174 ± 0.026 (g s^{-1}) VSP^{-1}).

Fig. 3 shows CO and NO average mass flow emission for the 14 VSP modes. As VSP mode increases, there is a tendency for CO emission to increase. Even with the ICE working under stoichiometric conditions and the closed-loop control of air/fuel ratio, in transient situations, which are typical in higher VSP modes, there is a tendency to slightly decrease air/fuel ratio, contributing for incomplete oxidation of fuel, enhancing CO formation (Fig. 3a).

Fig. 3b shows the NO mass flow emission in each VSP mode. The values are low (10^{-3}–10^{-4} g s^{-1}), as expected for spark-ignition

Table 3
Summary of fuel consumption, CO_2, CO and NO_x emission.

		Certification	On-road data	Deviation (%)
NEDC	Fuel consumption (l/100 km)	3.9	3.8	−3.2
	CO_2 (g km^{-1})	89	90	0.1
	CO (g km^{-1})	0.258	0.305	18.1
	NO_x (g km^{-1})	0.006	0.008	26.2

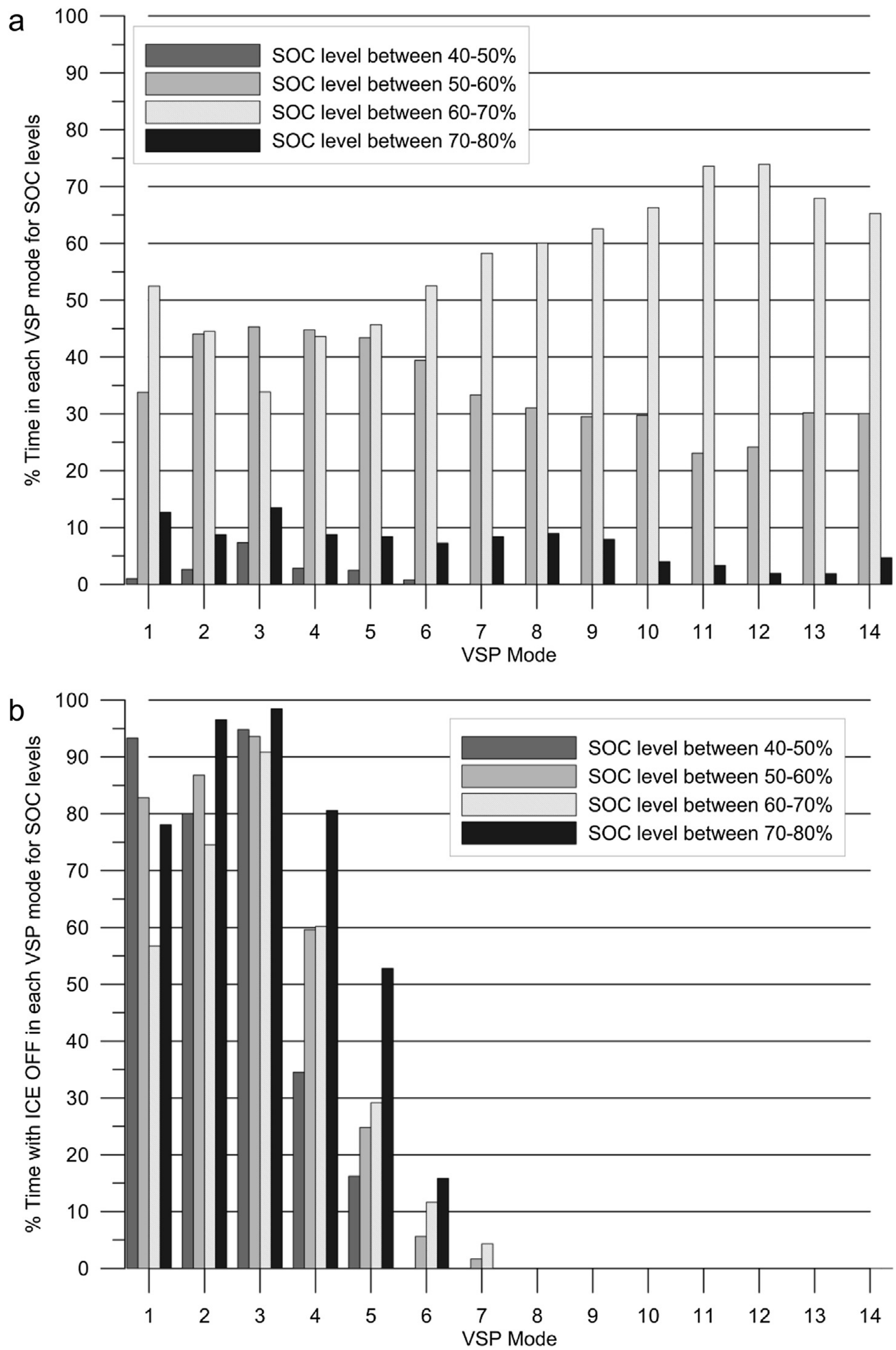

Fig. 4. (a) Percentage of time measured for each SOC level according to the VSP mode; (b) Percentage of time measured with ICE OFF according to VSP mode and SOC level.

engines. NO emission depends on distribution of the burned gas temperature and in the pressure inside the cylinder. In high VSP modes, there is an association with high load and high RPM conditions, hence the tendency for NO to increase with VSP, although the results found are very low.

3.2. Energy and environmental validation using NEDC certification data

The vehicle specific power modal analysis allows achieving an energy and environmental footprint, which is traduced by the mass flow of fuel, CO_2 and pollutant emission for a given VSP mode, independently of the driving cycle where the measurements were made. Also, each driving cycle has its own VSP time-based distribution, according to the speed, acceleration and road grade. To validate this approach the VSP methodology was used to calculate the fuel use and emissions of the test vehicle in the NEDC cycle and compare the values with certification data. Eq. (2) was used to estimate fuel consumption and pollutant emission for a given driving cycle [16]:

$$FC = \sum_{i=1}^{14} FC_i \times t_i \qquad (2)$$

where: FC: total fuel consumption for a given driving cycle; FC_i: fuel consumption for the VSP mode i for a given vehicle; t_i: time spent of VSP mode I for a given driving cycle.

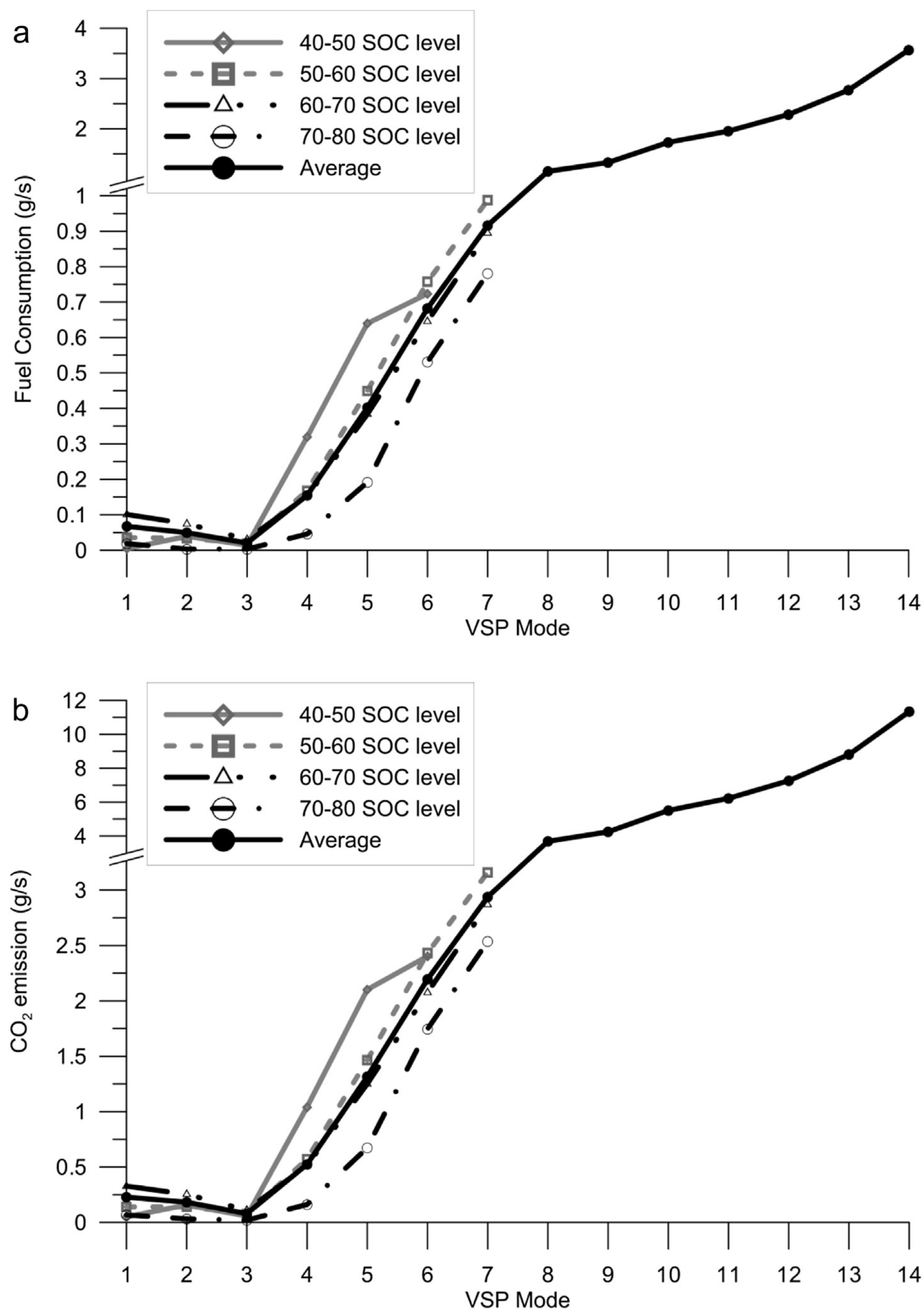

Fig. 5. (a) Fuel consumption (g s^{-1}) and (b) CO_2 emission rate (g s^{-1}) for different SOC levels as a function of VSP mode.

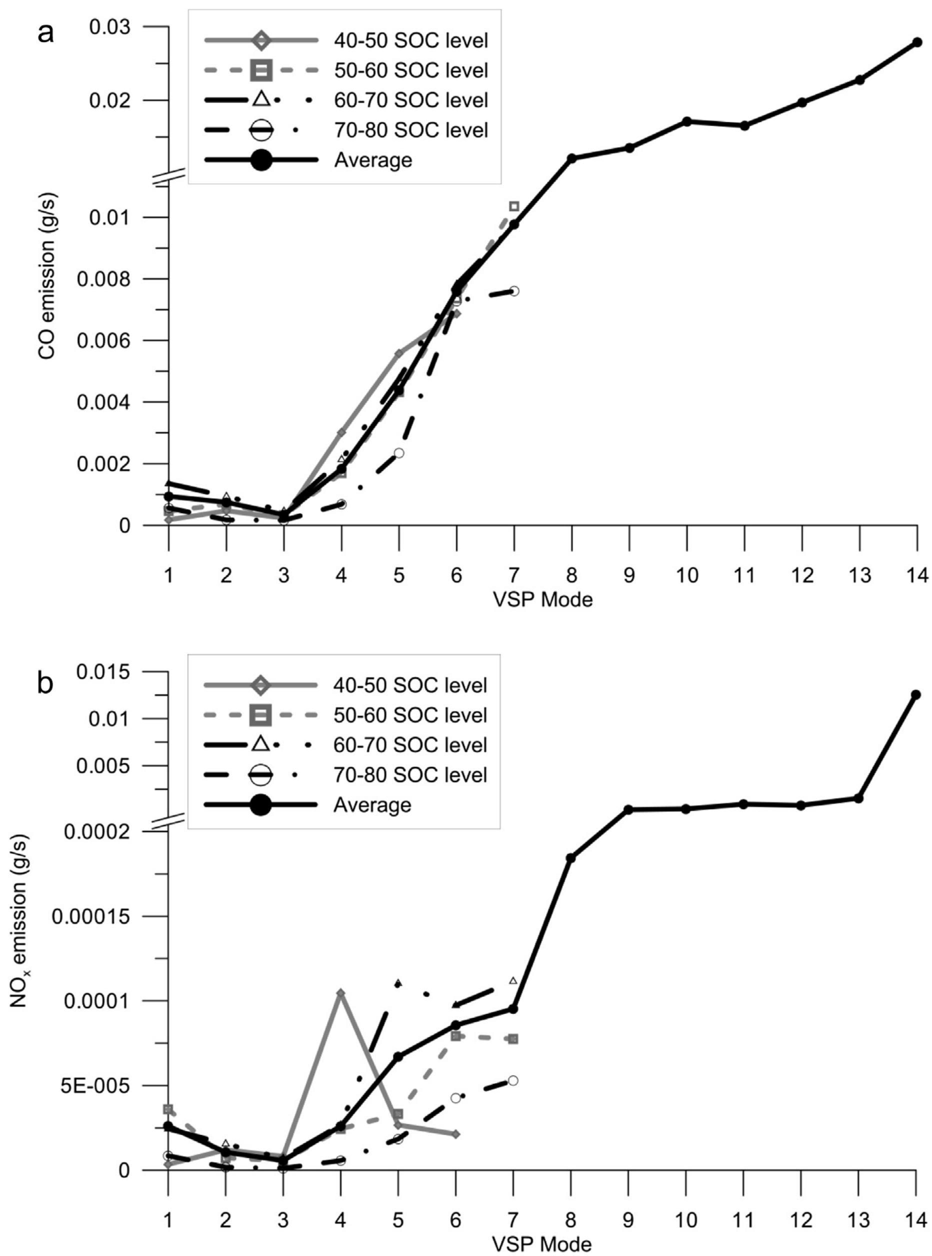

Fig. 6. (a) CO and (b) NO_x mass emission rates according to VSP mode and SOC level.

Eq. (2) uses measured on-road vehicle characteristics as present in Figs. 2 and 3 and the VSP time distribution of the NEDC (Table 2). Similar approach was used to estimate the pollutant emission. In that case, *FC* and FC_i were replaced by the correspondent pollutant.

Table 3 summarizes the estimated fuel consumption, CO_2, CO and NO_x emission for the vehicle Toyota Prius. From real-world driving cycles, energy and environmental analysis and the NEDC VSP distribution it was possible to replicate the certification of the vehicle. The value of the fuel consumption achieved was slightly lower than the certification, perhaps due to the ED mode preponderance on the on-road data. Certification procedures state that initial and final SOC should be the same [9]. During on-road measurements, maximum difference between initial and SOC never exceed more than 10% within trips. Trip average initial SOC was 57.8% and final SOC was 57.4%.

The results achieved for CO and NO_x are higher than certification, possibly due to the driving conditions, such as acceleration severity, road grade and traffic. It should be noticed that NO_x in certification refers to NO_2 equivalent, according to European Union regulations [18], and on-road measurements performed were carried as NO. Therefore, conversion of NO into NO_2 was performed correcting for the corresponding molecular weight.

Regarding the impact of ED mode and driving cycles – completely different from NEDC cycle – under the testing

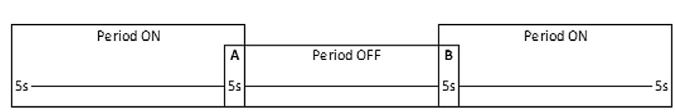

Fig. 7. Schematics of ON and OFF periods.

Table 4
Summary of the ratio of emission index.

		Period with internal combustion engine OFF				Average EI during ON period
		0–10 s	10–20 s	20–30 s	>30 s	
CO EI ratio	Average	1.24	1.35	1.26	1.63	0.01541
	95% CI	0.17	0.21	0.13	0.29	
NO_x EI ratio	Average	1.13	1.38	1.39	1.73	0.00035
	95% CI	0.10	0.13	0.25	0.39	
Coolant temp. difference (°C)	Average	−0.20	−1.22	−1.55	−2.40	N/A
	95% CI	0.07	0.21	0.38	0.32	

conditions, on-road data provides results in the same order of magnitude of certification data and a good estimate for fuel consumption, CO_2, CO and NO_x emission. Hence, data provided by Figs. 2 and 3 represent an energy and environmental footprint of the vehicle and can be used for other drive cycles, using VSP methodology and the correspondent time distribution in each VSP mode.

3.3. Hybrid management – ICE

The vehicle studied uses a power management based on the vehicle driving demand, hence the power is managed combining the energy from the ICE and from the electric motor, according to the battery SOC level.

According to Fig. 4a, for each VSP mode, the majority of time is spent within SOC levels between 50 and 70%, corresponding to the most representative points on energy and environment footprint of the vehicle. Regarding the driver display installed in the vehicle, 40–80% SOC corresponds to the lowest and highest limits, respectively.

Fig. 4b presents the measured distribution of ICE OFF (ED mode conditions) for each VSP mode, regarding SOC. ED mode only occurs up to VSP mode 7 and only between 50 and 70% SOC. The preponderance of ED is higher for lower VSP modes – as shown also on Fig. 1b – and is also higher for higher SOC levels. Comparing 70–80% SOC levels with the remaining, on average, on VSP mode 3, the higher SOC level represents an increase of ED time of more 5.8%, 67.4% on mode 4, 139.8% on mode 5 and 109.2% on mode 6.

Fig. 5a and b shows fuel consumption and CO_2 emission as a function of VSP and SOC. Both ICE ON and OFF points were considered for each SOC. Effect of SOC level is presented up to VSP mode 7, where ICE ON/OFF strategy is verified. For modes higher than 7 only an average of fuel consumption is presented due to lack of driving points for each condition.

According to Fig. 4b, as SOC level increase, percentage of time with ICE OFF is higher, hence fuel consumption tends to be lower. State of charge levels 50–60% and 60–70% have similar fuel consumption values. Considering only modes 1, 2 and 3 (correspondent to braking and idling conditions), fuel consumption is lower than average 48% for 40–50% SOC, 28.7% for 50–60% SOC and 83.2% for 70–80% SOC. For 60–70% SOC, it is 50.2% higher than average.

Regarding VSP modes 4 to 7, fuel consumption is, on average 57% and 9.7% higher for 40–50 and 50–60% SOC levels, respectively. It is 3.4% and 39.9% lower than average for SOC levels 60–70 and 70–80, respectively.

On Fig. 5b, CO_2 emissions follow the same trend of fuel consumption. Regarding VSP modes 4 to 7, CO_2 emission is, on average 56% and 9.7% higher for 40–50 and 50–60% SOC levels, respectively. It is 3.7% and 38% lower than average for SOC levels 60–70 and 70–80, respectively.

Fig. 6 presents CO and NO_x mass emission rates. From Fig. 6a, CO emission is 27.2% and 6.9% higher for 40–50% SOC and 60–70% SOC, respectively, comparing with average and considering only VSP modes 4 to 7. It is 1.6% lower than average for 50–60% SOC and 33.9% lower for 70–80% SOC.

Fig. 6b presents NO_x data according to the VSP mode and SOC level. Regarding modes 4 to 7, NO_x is 55.6% and 24.4% higher than average for SOC levels 40–50 and 60–70, respectively. For 50–60% and 70–80% SOC levels, emission is 20.7% and 61.4% lower than average, respectively. It should be noted that the measured values for NO_x are very low, close to the lower detection limit of the analyzer.

From Figs. 4b–6, it can be verified that under low power requirements, sole electrical propulsion has a great impact reducing fuel consumption and pollutant emissions, as seen. For VSP modes higher than 7 fuel and pollutant emission values can be found with more detail on Figs. 2 and 3.

The impact of ICE ON/OFF operation on emissions was analyzed in terms of the CO and NO_x emission index (EI), calculated as $mass_{CO}/mass_{fuel}$ and $mass_{NO_x}/mass_{fuel}$. For each engine OFF period the ratio of average EI between the first 5 s after engine OFF and the last 5 s before engine shut-off (B/A on Fig. 7) is calculated and grouped according to continuous engine OFF operating time. If the EI ratio is greater than one indicates that instantaneous emissions have increased due the shut-off of the engine. The total number of periods identified with this approach was over 150.

Table 4 shows that during the periods with engine OFF, as the engine is stopped for a longer period, the CO and NO_x emission index ratio tends to increase (up to 63% more CO EI for engine OFF periods longer than 30 s and 73% more NO_x EI for the same period), which might result from reduced efficiency of the catalytic converter due to cooling. The highest variation of coolant temperature in engine OFF periods was a 2.4 °C cooling. A potential improvement regarding pollutants in ON/OFF operation would be to minimize thermal losses on the catalytic converter.

4. Conclusions

This research work focuses on evaluating the effect of battery State of Charge in fuel consumption and gaseous pollutant emissions of a full Hybrid Electric Vehicle. Using a portable laboratory it was possible to characterize the vehicle energy and environmental footprint, according to the power demand, using VSP methodology. On-road energy rate and pollutant mass emission rates according to VSP mode were combined with NEDC VSP time distribution, making possible to compare certification data with collected data under real-world operation. It was observed a small reduction of 3.2% on fuel consumption using on-road data, probably due to impact of ED mode. Regarding pollutants, estimated CO was 18.1% higher than certification, as well as NO_x (+26.2%).

Under low power requirements, battery SOC level plays an important role on reducing fuel consumption and pollutant emission, namely on VSP modes 4, 5 and 6. For instance, on mode 4, the percentage of time with ICE OFF changes from 35% on 40–50% SOC to 81% on 70–80% SOC. Therefore, fuel consumption and CO_2 emission are higher for lower SOC levels.

Compared with average results, 40–50% battery SOC presented higher fuel consumption (57%) as well as higher CO_2 (56%), CO (27%) and NO_x (55.6%) emission rates. For battery SOC between 50 and 60%, fuel consumption was 9.7% higher, CO_2 was 9.7% higher, CO was 1.6% lower and NO_x was 20.7% lower than average results. For battery SOC between 60 and 70%, fuel consumption was 3.4% lower, CO_2 was 3.6% lower, CO was 6.9% higher and NO_x was 24.4% higher than average values. For battery SOC between 70 and 80%, fuel consumption was 39.9% lower, CO_2 was 38% lower, CO was 33.9% lower and NO_x was 61.4% lower than average values.

The impact of internal combustion engine OFF management was also addressed, being verified that as the engine was stopped for longer time periods, the CO and NO_x emission index ratio tends to increase (up to 63% more CO EI for engine OFF periods longer than 30 s and 73% more NO_x EI for the same period), which might result from reduced efficiency of the catalytic converter due to cooling. The highest variation of coolant temperature in engine OFF periods was a 2.4 °C cooling.

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